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EXPLORATION OF DOMINANT NEARSHORE CURRENT DIRECTIONS: AN INTEGRATED STUDY OF NUMERICAL SIMULATION AND CIVIC ENGAGEMENT ON MARINE DEBRIS HOTSPOT CHARACTERISTICS ALONG THE COASTAL ZONE OF TAINAN, TAIWAN

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Abstract
Marine debris is an escalating global environmental threat that jeopardizes ecological stability and maritime navigation safety. This study applies ocean numerical modeling and Lagrangian particle-tracking techniques to simulate the spatiotemporal drift pathways and dispersion behavior of debris under combined ocean current and wind forcing. Focusing on the Tainan coastline, a three-dimensional model was developed to analyze debris originating from major river outlets, providing a precise assessment of shoreline impacts and spatial distribution patterns. The results highlight significant accumulation of "hotspot zones" and forecast future drift trends. This study offers a scientific basis for policymakers to identify debris sources and destinations, thereby supporting targeted cleanup actions and enhancing civic responsibility through participatory education.
Keywords: *Numerical simulation, Lagrangian particle tracking techniques, drift, debris.*

1. Introduction

Over recent decades, the rapid accumulation of debris along global coastlines has severely impacted marine ecosystems. Studies reveal that pollution from marine litter results in an annual economic loss of 1% to 5% across industries such as fisheries, aquaculture, climate regulation, and recreation-equating to a staggering $50 to $2,500 billion USD annually [1, 2]. Consequently, marine pollution prevention has emerged as a critical global concern, demanding rigorous investigation and management efforts [3, 4].

The Taiwan Ministry of Environment classifies marine debris into nine major categories based on weight, while domestic NGOs utilize a streamlined 19-item classification adapted from the International Coastal Cleanup (ICC), including items such as plastic bottles, lids, food packaging, fishing gear, and miscellaneous waste. According to quarterly debris audits conducted by The Society of Wilderness (SOW) from 2018 to 2019, a total of approximately 646 metric tons of waste were recorded, with plastic items, styrofoam, and discarded fishing gear being the top contributors. Notably, 56% of this debris is concentrated along only 10% of Taiwan's shoreline, with Tainan ranking sixth in national volume.

Given plastic's dominance and environmental severity, international literature repeatedly emphasizes its peril to marine ecosystems, human health, and societal well-being. Land-based sources remain the primary origin of ocean waste, carried seaward via rivers, tides, or wind [5-7]. This study thus seeks to model and analyze the trajectories and coastal landings of debris emanating from riverine sources in Tainan, guiding cleanup strategies and cost reduction.

2. Methodology

We developed a three-dimensional Lagrangian particle tracking method to simulate marine debris drift and shoreline deposition. This technique integrates the Princeton Ocean Model (POM) [8, 9] for hydrodynamic simulation and wind field data from the Central Weather Bureau. The source points were

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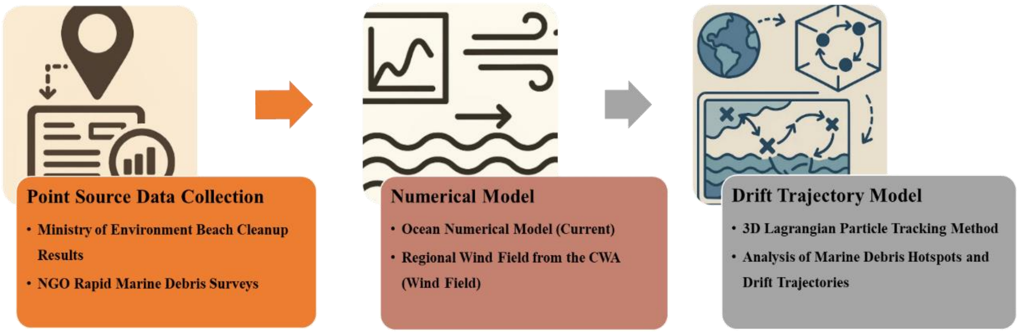

Figure 1. Flowchart of numerical simulation of marine debris drift trajectory

defined at river mouths in Tainan, informed by marine debris statistics from environmental agencies and NGOs, primarily based on beach cleanup datasets (see Figure 1 for the simulation flow diagram).

Ocean Current Modeling. Two-tier grid resolutions were employed to overcome limitations of boundary conditions in high-resolution ocean modeling:

- First Layer (Low-resolution Grid): Driven by regional oceanographic databases. The horizontal grid spacing for this layer is approximately 1 kilometer, with a time step of 30 seconds.

+ Bathymetry: ETOPO1 for macro-scale terrain; local ODB or survey data;

+ Atmospheric Forcing: CWA-WRF wind field data from the Central Weather Bureau;

+ Ocean Boundary Inputs: HYCOM data for sea surface elevation, vertical current profiles, temperature, and salinity.

- Second Layer (High-resolution Grid): Enhanced resolution using outputs from Layer 1 to refine boundary conditions and reduce error propagation. The horizontal grid spacing is 1/500° × 1/500° (approximately 0.2 kilometers), with a time step of 5 seconds.

Three-Dimensional Lagrangian Particle Tracking: The initial positions of the particles were set at the Coastal Cleanup Sites and River Estuaries (as shown in Figure 2), with 5,000 particles released from each location. For this simulation, particles were assumed to have the properties of wood, and the effects of biofouling and degradation were not considered. This parallelized model simulates debris movement by considering its physical properties and external forcing. Each particle is assumed to be influenced by current velocities and wind shear, with equations governing horizontal and vertical motion and settling velocity calibrated using empirical formulas. [6]:

$$\Delta x(t) = (u(t+\frac{\Delta t}{2}) + C_w U_{wind}(t+\frac{\Delta t}{2}))\Delta t \ , \qquad (1)$$

$$\Delta y(t) = (v(t+\frac{\Delta t}{2}) + C_w V_{wind}(t+\frac{\Delta t}{2}))\Delta t \ , \qquad (2)$$

$$\Delta z(t) = (w(t+\frac{\Delta t}{2}) - w_s(t+\frac{\Delta t}{2})) \ , \qquad (3)$$

In Equations (1) and (2), the variables $\Delta x(t)$, $\Delta y(t)$, and $\Delta z(t)$ respectively represent particle motion in the horizontal directions (m), while Z denotes motion in the vertical direction (m). The displacement of a particle at time t is described accordingly. The terms $u(t+\frac{\Delta t}{2})$ and $v(t+\frac{\Delta t}{2})$ indicate the horizontal velocity components (m/s) of the particle at the midpoint position ($\frac{\Delta t}{2}$). The parameter Δt refers to the time step (s), C_w is the wind drag coefficient, and U_{wind} and V_{wind} denote the wind velocity components (m/s) measured at 10 meters above the sea surface. The particle settling velocity w_s (m/s) is determined using the empirical formula proposed by Zhiyao, Tingting et al. (2008), as shown in Equation (4).

$$w_s = \frac{\upsilon}{2R}(p^*)^3(38.1 + 0.93(p^*)^{12/7})^{-7/8} \qquad (4)$$

In this equation, υ represents the kinematic viscosity of seawater ((m^2/s), R is the particle radius (m), and p^* is the dimensionless particle diameter

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(m), expressed as $2R(g(\rho_p - \rho_w)/\rho_p v^2)^{1/3}$, where ρ_p is the particle density (kg/m³), ρ_w is the seawater density (kg/m³), and g is the gravitational acceleration (m/s²).

3. Preliminary Findings

3.1 Empirical Observations

Data were extracted from the Taiwan EPA's coastal cleanup system, covering the period from 2017 to 2022. Bamboo and wood constituted ~87.77% of marine debris—primarily remnants from oyster farming structures. Other components included styrofoam (3.7%), PET bottles, nets, and metal cans. Table 1 summarizes the material breakdown.

Monthly data revealed site-specific debris types:

- January: Bamboo (Yuguang Island);
- February: Mixed waste (Guān Xì Platform);
- March: Glass and bamboo (Mashagou Beach);
- April: Bamboo and wood (Golden Coast);
- May: Mixed waste (Mashagou Coastal Recreation Area);
- June: Bamboo and wood (Golden Coast);
- July: other garbage, (Sunset Viewing Platform);
- August: Fishing gear (Yuguang Island);;
- September: Bamboo (Qiaotou Park);
- October: Bamboo and wood (Golden Coast);
- November: Bamboo and wood (Yuguang Island);
- December: Bamboo (Golden Coast).

Table 1. Composition and weight of marine debris along the Tainan coastline (2017–2022)

Type	Percentage (%)	Weight (tons)	Material
Paper Waste	0.30	0.010	Paper
Bamboo/ Wood	82.77	28.454	Bamboo/Wood
PET Bottles	1.16	0.400	Plastic
Fishing Nets	0.91	0.311	Polyester
Glass Bottles	1.68	0.578	Glass
Iron Cans	0.92	0.316	Iron
Aluminum Cans	0.43	0.149	Aluminum
Styrofoam	3.66	1.259	Polystyrene Foam

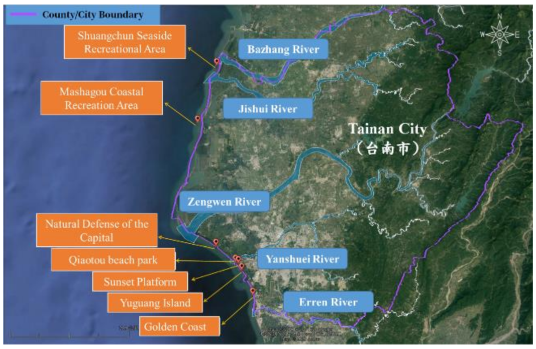

Figure 2. Coastal Cleanup Sites and River Estuaries along the Tainan Shoreline

3.2 Numerical Simulation

Field surveys and simulations were integrated to evaluate debris drift patterns. The model's performance was validated by comparing simulated water levels with observed data from the Jiangjun tide station, showing a Root Mean Square Error (RMSE) of approximately 0.02 meters and a correlation coefficient of about 0.98 (as shown in Figure 3). Students participated in interdisciplinary courses and beach cleanups at Qigu North Breakwater to reinforce concepts in coastal engineering and promote environmental awareness.

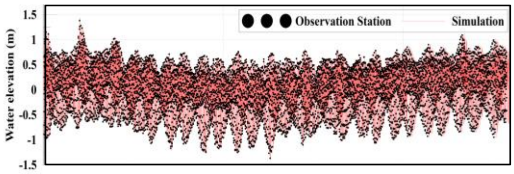

Figure 3. Water Level (Jiangjun Tidal Station)

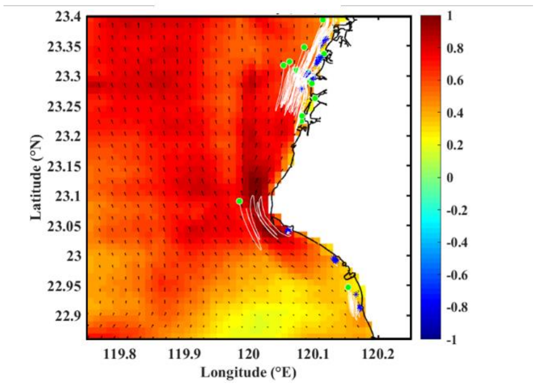

Figure 4. Drift Trajectories of Estuarine Debris

Simulations deployed virtual particles representing bamboo debris from major river outlets, calibrated to 2022 conditions. Results revealed clear drift differentiation:

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- Debris from northern rivers (Bajhang River, Jishui River, Zengwen River) was observed drifting northward;

- Debris from southern rivers (Yanshui River, Erren River) drifted southward.

Field verification matched the simulation:

- Golden Coast: Bamboo debris aligned with aquaculture regions;

- Guān Xì Platform: mixed waste linked to recreational or runoff sources.

(Refer to Figure 4)

3.3 Civic Engagement Activities

Educational initiatives involved teachers and students in cleanups and debris classification. Workshops differentiated between marine litter and driftwood.

- Qigu North Breakwater: Lightweight debris such as fishing gear and oyster racks;

- Jiangjun Harbor: Driftwood fragments;

- Yuguang Island (Crescent Bay): Dry reeds, fishing floats, household containers.

(Refer to Figure 5 - 7)

Figure 5. Accumulation of Fragmented Driftwood along the Northern Breakwater of Jiangjun Fishing Harbor

Figure 6. Dried Reeds and Domestic Waste along the Shoreline of Qigu Crescent Bay

Figure 7. Distribution of Lightweight Bamboo Structures and Fishing Gear along the Northern Breakwater of Qigu

Community exhibitions in July-August 2024 showcased creative works made from recovered debris (Figure 8-9). Public engagement included identifying debris types and locations. Observations emphasized driftwood, fishing gear, glass bottles, and disposable utensils. Styrofoam was notably absent in Jiangjun.

Figure 8. Creative Works Made from Driftwood by Members of the Teacher Community

Figure 9. Engaging Exhibition Visitors in Identifying Marine Debris Distribution along the Coastal Beaches

These participatory activities combined scientific modeling with practical observation, enhancing public environmental literacy and material understanding for future professional development.

4. Conclusions

In response to the growing threat of marine debris, this study integrates a self-developed three-dimensional Lagrangian tracking method with the Princeton Ocean Model and wind field data to simulate drift dynamics and spatial dispersion along Tainan's coast. Empirical data showed that bamboo waste dominates the marine debris profile (87.77%), largely originating from oyster farming operations.

Numerical results demonstrated a distinct north-south drift pattern based on debris origin. Validation with field data confirmed hotspot concentrations at Golden Coast and Guān Xì Platform. This alignment supports targeted interventions for debris removal and cost reduction.

Furthermore, the study's integration of academic curricula, beach cleanups, and public exhibitions fostered civic participation, enriching environmental consciousness and extending research impact beyond academia.

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